



Observation of Wind-Loading Influences in Nonconcentric Radial Root Growth in Two Maple Species

By Jason Grabosky

Abstract. In 2010 and 2016, *Acer saccharinum* and *Acer rubrum* roots were harvested and processed into transverse serial sections to observe cross-sectional radial growth patterning in response to wind. Trees on the edge of a plantation and from interior positions were selected, and windward/leeward roots were targeted for a comparative assessment. While some observations were suggestive of a response to wind exposure, they were not definitive. Particularly in the windward versus leeward comparison within either edge or interior ground in terms of root size or radial growth pattern, there were no differences observed. In general, the loss of observed upward radial growth bias very closely coincided with the ending of the Zone of Rapid Taper in the architecture of the root plate.

Keywords. Edge Effect; Wind Exposure; Zone of Rapid Taper.

INTRODUCTION

Trees in developed landscapes provide many services but can cause damage to surrounding structures. Damage to pavement is common when trees grow over time to larger sizes, while the adjacent pavement surface ages and breaks down. While we can design for pavement longevity when tree roots are expected to share the same soil volume that supports the pavement (Grabosky and Bassuk 2017), such plans place two landscape design components with very different service-life expectations into one design plan. As the pavement surface will need replacement over time, the tree-pavement design ought to allow for resurfacing without the need to remove major roots of the tree architectural system. Damage and removal of large roots near the trunk during pavement repair can have impacts on tree wind-firmness and tree vitality, since large sections of fine root mass ultimately connect through the large roots of the root plate (Smiley 2008).

As major lateral roots grow, they must displace soils in axial penetration for colonization and in radial expansion during perennial secondary growth. Pavement design must account for root displacements, particularly from radial growth, and understanding the directionality of that growth is desirable for informing loading models in pavement design and ultimately field practices in tree-pavement management. Similarly, as tree care professionals consider

and assess tree risk in the developed landscape, root-zone inspections can benefit from a greater knowledge base of how root systems may or may not reflect wind-loading patterns on a site.

As trees intercept wind loads, energy not dissipated by damping or countered by trunk ballast is transferred from trunk to root system and ultimately transferred to soil (Stokes 2002) while generally shifting from a central shaft of vertical orientation to several organs of horizontal and/or oblique spread. While the mechanisms for loads to move from trunk to root are common to both forest-grown and urban trees, the competition for light, wind patterns, and resulting canopy form can differ greatly. These observed changes in canopy form and thus load interception would benefit from a larger research foundation to link changes to root architectural development.

Root-system architectural forms of common North American street trees often fall within compressive buttressing or flat, plate-like types (Vogel 1996; Mattheck et al. 2015). Within those root architectural forms, a Zone of Rapid Taper (ZRT) has been discussed (Eis 1974). The ZRT has been defined to describe near-trunk root-system architecture wherein roots shift from few, large organs in cross-sectional view to much smaller roots which do not reduce in size over a unit distance from the tree trunk. It stands to reason that the ZRT could inform the distance

between the tree trunk and the pavement edge to accommodate open soil surfaces for normal air and water exchange and accommodate the large soil displacements from root growth which would uplift and disrupt pavement surfaces. As such, study observations linking pavement damage to street tree proximity (Barker 1989; Mudrick 1990; Randrup et al. 2001; Costello and Jones 2003) can be rephrased as a possible accommodation of the ZRT. Consideration of the ZRT in placement distance or proximity to pavement can yield significant reductions in the displacement of pavements, which develop tripping liabilities and result in premature pavement replacement from a lifting failure. Otherwise, specific design responses to accommodate such ZRT impacts in close-proximity pavement can be advanced where there is a lack of space in the shared infrastructure demands in an urban environment.

In the ZRT, there are several observations of nonconcentric root growth displaying a distinct upward or downward bias in growth in reference to the original root growth axis, which changes to an ultimate concentric or centered position with increasing distance from the trunk of the tree (Fayle 1968; Nicoll and Ray 1996; Coutts et al. 1999; Di Iorio et al. 2007; Grabosky et al. 2011). Observations have been more or less comprehensive, ranging from two roots on one tree (Fayle 1968) to an organized large study format (Nicoll and Ray 1996). Possible mechanical explanations, particularly in conifer species in forest tree situations, for nonconcentric growth patterning in radial secondary root growth and the resulting root cross-sectional shapes in shallow roots close to the trunk have been advanced (Eis 1974; Coutts 1983; Coutts et al. 1999; Weber and Mattheck 2005). Discussions of loading on buttress roots and the subsequent development of a root plate (Fayle 1968; Coutts 1983; Coutts 1987; Vogel 1996; Gartner 1997; Nielson 2009) are consistent with an observation of upward growth of root plates near tree trunks. This zone of large roots with an upward radial bias tapering to a more rope-like morphology with distance from the trunk (Fayle 1968; Eis 1974; Wilson 1975; Coutts et al. 1999) operatively defines the ZRT. In all of the mentioned discussions, the presumed loading was resultant of wind interception of tree canopy translated from a bending trunk into the root system. The larger roots in the ZRT have been thought to provide stiffness at the root-trunk transition (Coutts 1987), so looking closely at both the growth patterning in cross section and the size changes in the ZRT was of specific interest.

Pragmatically, it would make sense for roots to exhibit an upward growth bias near the trunk in large roots. The energy needed to displace soil is generally less in the upward direction, where the unit weight of soil as a force is the main impediment once any matrix shear strength in displacement is overcome. In all other directions, the forces are larger due to relatively unlimited distances of

soil to factor into any displacement and soil failure models. Observation of increased tensile strength as root diameter decreases can be accompanied with increases of cellulose content as a component percentage of root tissue (Genet et al. 2005; Zhang et al. 2014). Root tissues have also been generally observed to have a presence of parenchyma versus differentiated fibers in the root tissue organization (Esau 1977) consistent with an occurrence in the supportive matrix of soil (versus gravitational self-loading and support in aerial portions of the shoot and canopy). Such changes in tissue organization suggest the role in tensile loading in root anchorage and would bias toward a more upward growth investment in the transition from the trunk to the root system.

The suggested influence of wind loading on root growth patterning can inform the question of pavement design, as urban trees are often subjected to building-induced wind patterns, or are planted as lone figures within a variable wind field, rather than in a forest stand configuration. The two studies described here attempted to observe in an organized manner the patterning of radial root growth on a site with a gradient of wind exposure from a single direction. This information may inform future modelling for pavement designs which support both safe pavement and root colonization over specific service time intervals (Grabosky and Gucunski 2011). In so doing, we also are able to add to the understanding of the ZRT to support the assignment of construction protection and design distances between structures and trees over time as the tree grows.

The studies take advantage of an established experimental grove in Shalersville, Ohio as part of the Davey Tree Research Institute programs. The trees were allowed to be destructively harvested during a series of International Tree Biomechanics research weeks which culminated with a research symposium. The presented work compares the characteristics of root growth between grove interior trees and those on the windward edge of the grove. Roots originating on the windward and leeward sides of trees were used to describe radial root growth dissymmetry in two species, *Acer saccharinum* and *Acer rubrum*.

MATERIALS AND METHODS

The trees used in this study were planted as single-species orchard plots on the west side of the research grove. The research plantation grove managed for research by Davey Tree Expert Co. is located in Shalersville, Ohio (41.2333°N, -81.1525°E) on Ravenna silt loam, 2 to 6% slope (ReB), with site densities of 1.09 Mg/m³ in the surface 8 cm, increasing to 1.62 Mg/m³ at 23 to 31 cm depth, measured approximately 90 to 110 m from study trees on the research plot site (Soil Survey Staff 2018; John Siefer Personal Communication 2018). The prevailing wind on the site comes from the west, so trees on the western edge were

exposed to direct winds from one direction but protected from any occasional winds from all other directions. Tree species selected were *Acer saccharinum* (2010 harvest) and *Acer rubrum* (2016 harvest) as part of the first and third Tree Biomechanics events. Species selection was based on availability in the edge and interior locations and replicate counts available for testing. Given the specific realities of this managed research tree orchard design, such as impacts of light access (not a canopy closure situation based on stand density spacing) and slope impacts and soil differences (not present in a planned grid design), there was as much of an isolation of wind effect as could be reasonably possible in any planned study.

In the 2010 study, eight *Acer saccharinum* trees were chosen, with five wind-exposed edge trees (31 to 43.4 cm diameter at breast height [dbh], mean 36.6 cm) and three interior trees (28.5 to 40.4 cm dbh, mean 33.9 cm). Dbh was measured with a cloth diameter tape at 1.37 m from the ground. Entire root plates were air excavated, and roots were then identified for harvest at cardinal directions to allow selection of a single windward, single leeward, and two roots perpendicular to the wind pattern, for a targeted four roots per tree. Actual counts (Table 1) reflect the occasional absence of roots in specific orientation during field collection or inability to trace a single root axis due to collection damage or anastomosis. These roots were then excised from each tree.

Roots were labeled and surface direction was marked with logging paint to properly orient the root during serial sectioning. After brushing clean, the roots were processed into 40 to 60 mm serial sections, with an additional saw kerf of 8.34 mm. The proximal face of the section was measured for total vertical diameter and the distance of top and bottom edges from the initial growth axis. When needed, the surface face of the section was sanded to obtain visual location of the initial growth axis. Section faces were cataloged as a function of distance to the trunk edge,

developed after accounting for the initial root harvest cut distance from the trunk. Measurements were used to determine total root vertical diameter and observations in radial growth root symmetry. Root sections identified the original growth axis and then the distance to the top and bottom edge of the root was measured.

Tracking the section face distance from the trunk and the point where the upward growth was no longer greater than the downward growth was defined as the point of upward bias transition (UBT). The UBT distance from trunk to a variably downward bias or concentric growth pattern was noted. In most instances, no downward bias was observed in the section thickness that was used. Initial root diameter in the vertical direction was recorded at 10 cm from the trunk. Notes were made on a loss of rapid taper, in this case defined as a < 5% difference in vertical cross section between successive section diameter measures moving in a distal direction. The distal face of the last tapering section was used to define the distance for the ZRT. ZRT has often been referenced to an arbitrary distance from the trunk (Wilson 1964; Lyford 1980; Danjon et al. 1999).

In the 2016 harvest, eight *Acer rubrum* trees were chosen, with four wind-exposed edge trees (dbh range 27.43 to 43.69 cm, mean 35.43 cm) and four interior trees (dbh range 28.45 to 37.08 cm, mean 31.81 cm). A single windward and a single leeward root (rather than full plate excavation prior to root selection) were identified and air excavated for removal and measurement. In some cases, where branching occurred very near the trunk, multiple axes were sectioned. Table 2 details the total number of roots sectioned in either direction. The study followed the same general protocols as the 2010 harvest except that the roots were processed into varied serial section thicknesses using saws of different kerf thickness.

Analysis was developed in Minitab 14 (Minitab Inc. State College, PA U.S.A.). General descriptive statistics by

Table 1. Measured root characteristics for nonconcentric radial growth patterns on the windward edge and within the interior of an experimental grove of *Acer saccharinum* (dbh 28 to 43 cm) in the 2010 harvest. Means and (standard deviation) for root position in reference to wind loading pattern for initial root size at 10 cm from trunk edge and point of transition from an upward growth dissymmetry to either a downward bias or concentric growth in transverse section view (UBT) as a distance from trunk edge.

		Windward	Leeward	Perpendicular
Plantation edge <i>N</i> = 5 trees	Root diameter (mm)	127 (43)	120 (32)	123 (58)
	UBT distance (mm)	594 (299)	531 (182)	514 (266)
	Replicate count	3	5	8
Plantation interior <i>N</i> = 3 trees	Root diameter (mm)	139 (24)	126 (58)	116 (81)
	UBT distance (mm)	197 (190)	366 (111)	456 (336)
	Replicate count	3	3	5

Table 2. Measured root characteristics for nonconcentric radial growth patterns on the windward edge and within the interior of an experimental grove of *Acer rubrum* (dbh 28 to 44 cm) in the 2016 harvest. Means and (standard deviation) for root position in reference to wind loading for initial root size at 10 cm from trunk edge, UBT distance, UBT root diameter, and Zone of Rapid Taper (ZRT) distance from trunk edge. In a comparative distance from the UBT to ZRT, a positive number indicates UBT was beyond the taper zone, whereas a negative number indicates the UBT occurred before taper ended.

		Windward	Leeward
Plantation edge <i>N</i> = 4 trees	Root diameter (mm)	201 (62.2)	92 (14)
	UBT distance (mm)	653 (215)	881 (365)
	Root diameter (mm) at UBT	95 (36)	64 (18)
	ZRT: trunk to end of taper (mm)	862 (314)	791 (339)
	Distance UBT from ZRT (mm)	-208 (283)	90.6 (157)
	Replicate count	4	6
Plantation interior <i>N</i> = 4 trees	Root diameter (mm)	112 (58)	149 (33)
	UBT distance (mm)	748 (224)	775 (132)
	Root diameter (mm) at UBT	52 (11)	71 (14)
	ZRT: trunk to end of taper (mm)	726 (205)	825 (75)
	Distance UBT From ZRT (mm)	21 (129)	-50 (188)
	Replicate count	4	5

root location and wind exposure group were developed. Inflection points from upward to downward to concentric root growth were developed and similarly described. One-way ANOVA was used to directly compare windward and leeward roots within exposure categories. General Linear Models were used to compare root position (including the perpendicular roots in the first study) while comparing edge versus interior trees. Observations between the two studies were not directly compared. Given the low replication within each category, normality of the data was assumed.

RESULTS

Within a General Linear Model from the 2010 *Acer saccharinum* cohort, there were no significant differences ($P = 0.780$) found in UBT distance based on direction of the root in reference to the prevailing wind pattern (Table 1). There were few significant relationships developed from the data set of harvested roots. The end of the ZRT was noted to stop in the sections including the UBT in all but four cases. In those cases, the ZRT ended within 60 mm of the observed UBT. Table 1 details the findings from the first harvest of *Acer saccharinum*, showing a generally wide measurement variance on initial root size or distance of the UBT from the trunk edge. General observations noted that the plantation-edge trees showed roots with less immediate branching, and those against the trunk were easily isolated as a specific root base–trunk transition (Figure 1).

Trees within the interior of the plantation showed prolific branching and grafting for a dense network of axes within the root plate area (Figure 2).

There was a fair amount of variability in a limited number of harvested roots, thus a suggestive difference in the observed UBT comparing edge trees and interior trees was not significant ($P = 0.061$) despite all edge tree root categories having a mean UBT further from the trunk. One windward root and three perpendicular roots were not reported due to multiple growth axes anastomosing which prevented a clear measurement. One additional windward root was harvested in a short section, due to machine breakage which did not show a UBT, and was discarded. In one-way ANOVA tests, root diameter was not related to tree position of edge or interior ($P = 0.87$) nor by root growth



Figure 1. Excavation of roots of *Acer saccharinum* on the edge of the plantation showing less immediate large branching and clear origination location at the trunk transition.



Figure 2. Excavation of roots of *Acer saccharinum* within the interior of the plantation showing increased branching and grafting near the trunk.

direction ($P=0.875$). No relationship was observed between UBT and dbh. While there was no observed relationship between root diameter and dbh in the edge-tree group, within the interior-tree group, the windward and leeward roots increased in diameter as dbh increased.

The 2016 harvest was able to capture a balanced tree replicate structure, but only windward-leeward roots were collected (Table 2). Plantation-edge windward roots were observed to have a shorter UBT distance and thicker roots on average. In three leeward roots, there was observed branching of the root within 250 mm of the trunk, so multiple replicates on those cases are reported.

In six cases, multiple roots beyond the ones identified and reported here had anastomosed to a point where there



Figure 3. Root cross section showing the anastomosis, or fusing, of multiple roots into one contiguous external surface. Horizontal distance in the center root structure is 26 cm.

was a continuous outer root epidermal zone which functioned as a single “aggregated root” in surface contour, often with included soil sections where roots were initially separated (Figure 3).

This yielded a structure rather than a contiguous root wood material which would have an impact on mechanical interpretations at the point of root-to-trunk transition. Additionally, with the rapid initial branching on several samples, an oval or circular cross section would be a very large assumed simplification in any analysis. Of the six cases of this anastomosis, three were on windward side of plantation-edge trees, one was leeward in an interior grove tree, and two were windward on interior grove trees. While not exhaustively measured, the size of the “root” area often doubled or tripled that of the targeted root axis that was traced over the distance beyond the point where such roots became individual and separate axes of growth. Whole cross sections measured by d-tape as an estimate increased the apparent single root diameter by 25 to 100%, resulting in a radically increased apparent root area (as calculated from the measured diameter as a circle of a single structure versus multiple roots) which also would influence the associated surface area in contact with the soil.

There was no significant difference in the initial root diameter among the interior trees, nor was there a difference between edge and interior trees in the General Linear Model total comparison ($P=0.477$). There were distinctly larger root diameters on the windward side of trees on the plantation edge, which were subjected to direct wind loading as the leading edge of the canopy. However, within the General Linear Model, the result was a lack of overall difference comparing windward and leeward root size ($P=0.123$).

No significant differences in UBT distance were observed by tree location or root location, and root diameter at the UBT reflected the same relationship as the initial root diameter. The differential distance between ZRT distance and UBT distance were not informative due in part to high variability complicated by low replication. Proximity of the two measures was noticeably closer in the plantation interior.

DISCUSSION

The study provided observations in maple trees in the effort to better describe any patterns of radial root growth near the tree trunk in the Zone of Rapid Taper resulting from a convenient testing situation with a wind-field influence. If patterns were obvious and consistent, they could have then been used to develop modeling inputs for testing root-pavement design systems. That was not the case with the data set collected, particularly in comparing the windward to the leeward roots. Time limitations and the available field subjects within the plantation grid during the

2010 Biomechanics Week event prevented collection of a larger data set, and this may have influenced the ability to gain clear comparative differences within the testing groups. Also, with more time and funding, finer detail in branching character and cross-sectional shape profile and area data could have been developed. While the replication is low and the final results are not definitive, it is important to remember that the trees which were destructively harvested were standing and in sound condition and selected to make the specific observational comparisons. Too often we can only observe failed trees and make inferences without having information from trees which did not fail, since it takes decades (over 50 years in this case) to develop a testing block from which to attempt this study.

In general, there were no observations of specific growth shape profiles such as T-beam or I-beam/figure-eight roots as noted in other works (Nicoll and Ray 1996; Coutts et al. 1999; Weber and Mattheck 2005). However, it is important to note those studies were looking at gymnosperms in the *Pinaceae*, whereas this study used species in the *Sapindaceae* with very different wood organization and vascular tissue differences. A generally greater ZRT and UBT distance was observed from the trees in the 2016 *Acer rubrum* harvest as compared to the 2010 *Acer saccharinum*.

The study's observations are certainly consistent with a pattern of growth which is influential on load transfers in the redirection from trunk to roots. While the data set is too small to yield any conclusive observations, it is interesting in the 2016 *Acer rubrum* harvest to observe plantation-edge windward roots have a slightly shorter UBT distance with thicker roots on average. Coupled with the anastomosis effect and rapid branching of the windward roots, any consideration of the influence of the collective (or aggregated) root geometry demonstrates the importance of dimensional size, which would contribute to an argument of added stiffness (Coutts 1987) with a caveat that the external surface of the root belies a potentially discontinuous volume of heterogeneous tissue structure rather than a material.

As a pattern of nonconcentric radial growth, the study's observations were consistent with a tensile loading emphasis. This finding is further bolstered by a generally short (within a single section thickness) downward bias, to the point of no observation prior to concentric root development and associated loss of taper. The differences in UBT comparing the perpendicular roots to the windward and leeward roots in the 2010 silver maples are consistent with the observations of Nicoll and Dunn (2000) inasmuch as the roots perpendicular to the wind were different than those in the windward/leeward orientation. It supports a notion that the flexing of roots (compression down and a pulling outward) produces a difference in growth patterns from the roots if perpendicular to a prevailing wind. Urban trees can be seen to have impacts from specific wind

directions in a designed space, or take wind from any direction if planted as an isolated specimen rather than in a more natural grove configuration. With that view, the data could be helpful in future studies to frame the design and observation methods for future opportunities.

While sectioning did not go down to an anatomic analysis, observations from both harvests in the gross scale are consistent with observations in tissue organization and morphology discussed in Christensen-Dalsgaard et al. (2008), where growth in proximal zones of the buttress roots is highly mechanically loaded from initial growth, whereas further out, the mechanical loads become less influential during early tree growth stages. That influence further out on the root increases progressively over years of growth of the tree above ground, both in the change in trunk proximity with growth, and with the stature of the tree and its interception of wind.

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Jason Grabosky (corresponding author)
Rutgers University
Dept. Ecology, Evolution and Natural Resources
14 College Farm Road
New Brunswick, NJ 08901, U.S.A.
848-932-0050
grabosky@sebs.rutgers.edu

Résumé. En 2010 puis en 2016, des racines d' *Acer saccharinum* et d' *Acer rubrum* furent récoltées et transformées en sections séries transversales afin d'observer la modélisation de la croissance transversale radiale en réaction au vent. Des arbres situés en bordure d'une plantation et d'autres localisés à l'intérieur de celle-ci furent sélectionnés et des racines croissant au vent et sous le vent furent prélevées en vue d'une analyse comparative. Bien que certaines observations suggéraient une réaction à l'exposition éolienne, elles ne furent pas concluantes. Aucune différence ne fut observée, particulièrement pour la comparaison entre les racines croissant au vent et sous le vent en termes de la grosseur des racines ou de la modélisation de la croissance radiale et ce,

sans considération de la provenance des échantillons en bordure ou à l'intérieur de la plantation. De manière générale, la perte de la tendance à la hausse de la croissance radiale observée coïncidait étroitement avec la fin de la zone de défilement rapide dans l'architecture du plateau racinaire.

Zusammenfassung. In 2010 und 2016 wurden *Acer saccharinum* und *Acer rubrum* Wurzeln geerntet und in traverse Sektionen geschnitten, um die radialen Wachstumsstrukturen mit ihrer Reaktion auf den Wind zu beobachten. Es wurden Bäume von den Rändern und aus der Mitte der Pflanzung ausgewählt und für eine vergleichende Untersuchung wurden lee- und luvseitige Wurzeln ausgewählt. Es gab keine beobachteten Unterschiede besonders im Vergleich zwischen den lee- und luvseitigen Ausrichtungen innerhalb entweder Rand- oder Mittelposition in Bezug auf die Wurzelgröße oder radialen Wachstumsstrukturen. Allgemein war der Verlust des radialen Wachstums sehr eng verbunden mit dem Ende der Zone des radialen Wachstums in der Architektur der Wurzel.

Resumen. En 2010 y 2016, raíces de *Acer saccharinum* y *Acer rubrum* fueron cosechadas y procesadas en secciones transversales en serie para observar patrones de crecimiento en respuesta al viento. Se seleccionaron árboles en el borde de una plantación y en posiciones interiores; igualmente se seleccionaron raíces de barlovento / sotavento para una evaluación comparativa. Si bien algunas observaciones sugirieron una respuesta a la exposición al viento, ellas no fueron definitivas. No se observaron diferencias particularmente en la comparación de sotavento versus sotavento dentro del borde o del interior en términos de tamaño de la raíz o patrón de crecimiento radial. En general, la pérdida del sesgo de crecimiento radial ascendente observado coincidió muy estrechamente con el final de la Zona de Reducción Rápida en la arquitectura del plato de la raíz.